Gravitational waves from the early Universe: where do predictions and experiments stand?

Alessandra Buonanno

Institut d'Astrophysique de Paris (CNRS) & California Institute of Technology

Content:

- **How gravitational waves can be used as a probe of the early Universe**
- **Capabilities and time scales of current and future experiments**

Cosmo02, International Workshop on Particle Physics and the Early Universe, Chicago

International network of earth-based GW interferometers

LIGO at Livingston (Lousiana) ⇒

⇐ LIGO at Hanford (Washington State)

Virgo (France-Italy) ⇒

GEO 600 (UK-Germany)

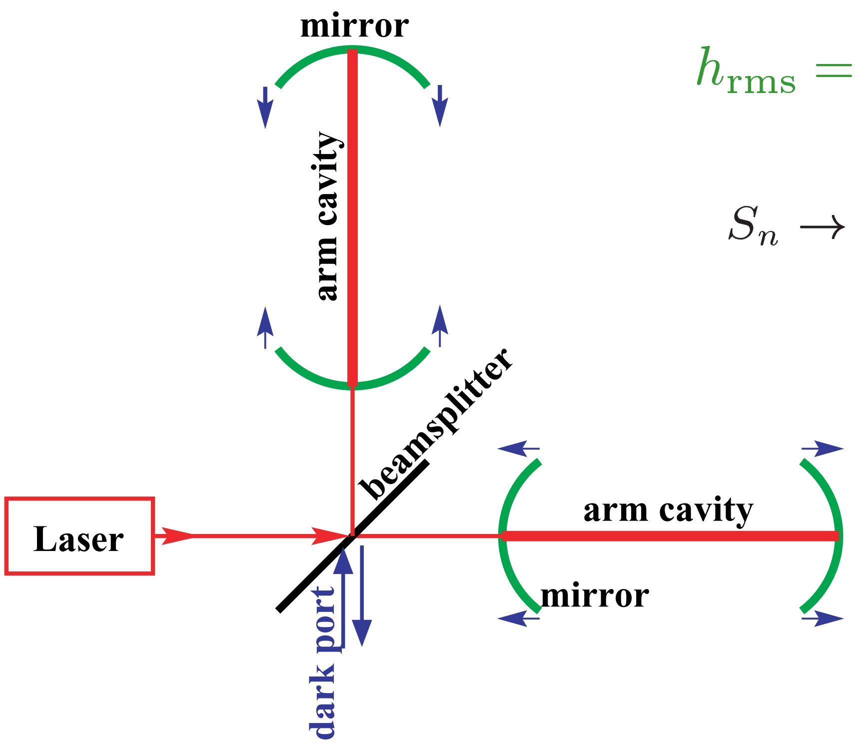
TAMA 300 (Japan)

Resonant bar detectors

Nautilus (Rome) Explorer (CERN)

Allegro (Louisiana) Niobe (Perth) Auriga (Padova)

Earth-based GW interferometers (frequency band: $10 - 10^4$ Hz)



$$h_{\rm rms} = \sqrt{S_n(f)\,\Delta f} = \frac{\Delta L}{L}, \qquad h_n \equiv \sqrt{S_n(f)}$$

$S_n \rightarrow$ noise power per unit frequency, $\Delta f \rightarrow$ bandwidth

$L \rightarrow$ arm-cavity length (4 Km)

LIGO-I/Virgo at $f \sim 100$ Hz: $\Delta L \sim 10^{-18}\,\mathrm{m}$

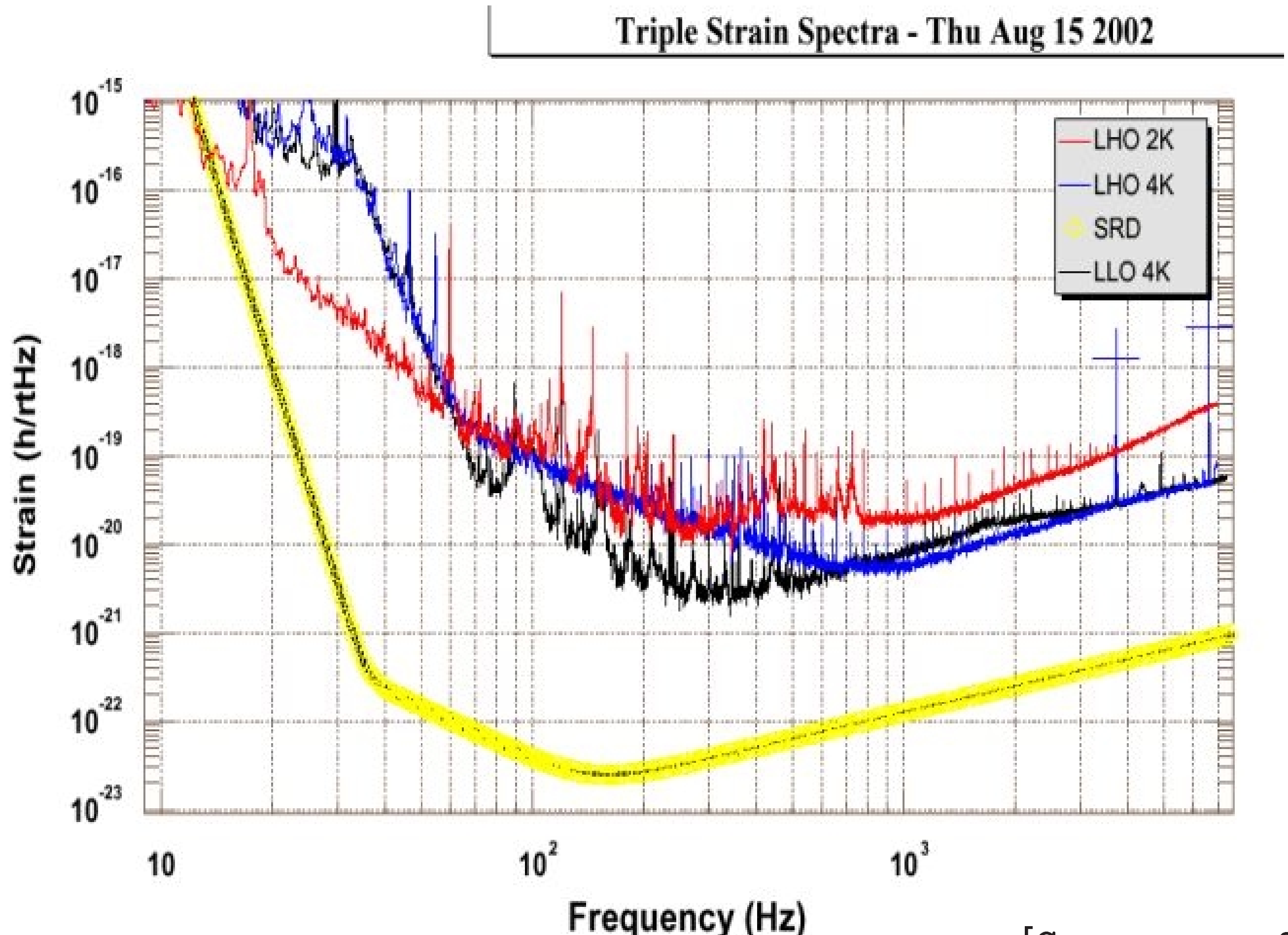
$F \sim 10^{-11}\,\mathrm{Newton}$

LIGO-II at $f \sim 100$ Hz: $\Delta L \sim 10^{-19}\,\mathrm{m}$

$F \sim 10^{-12}\,\mathrm{Newton}$

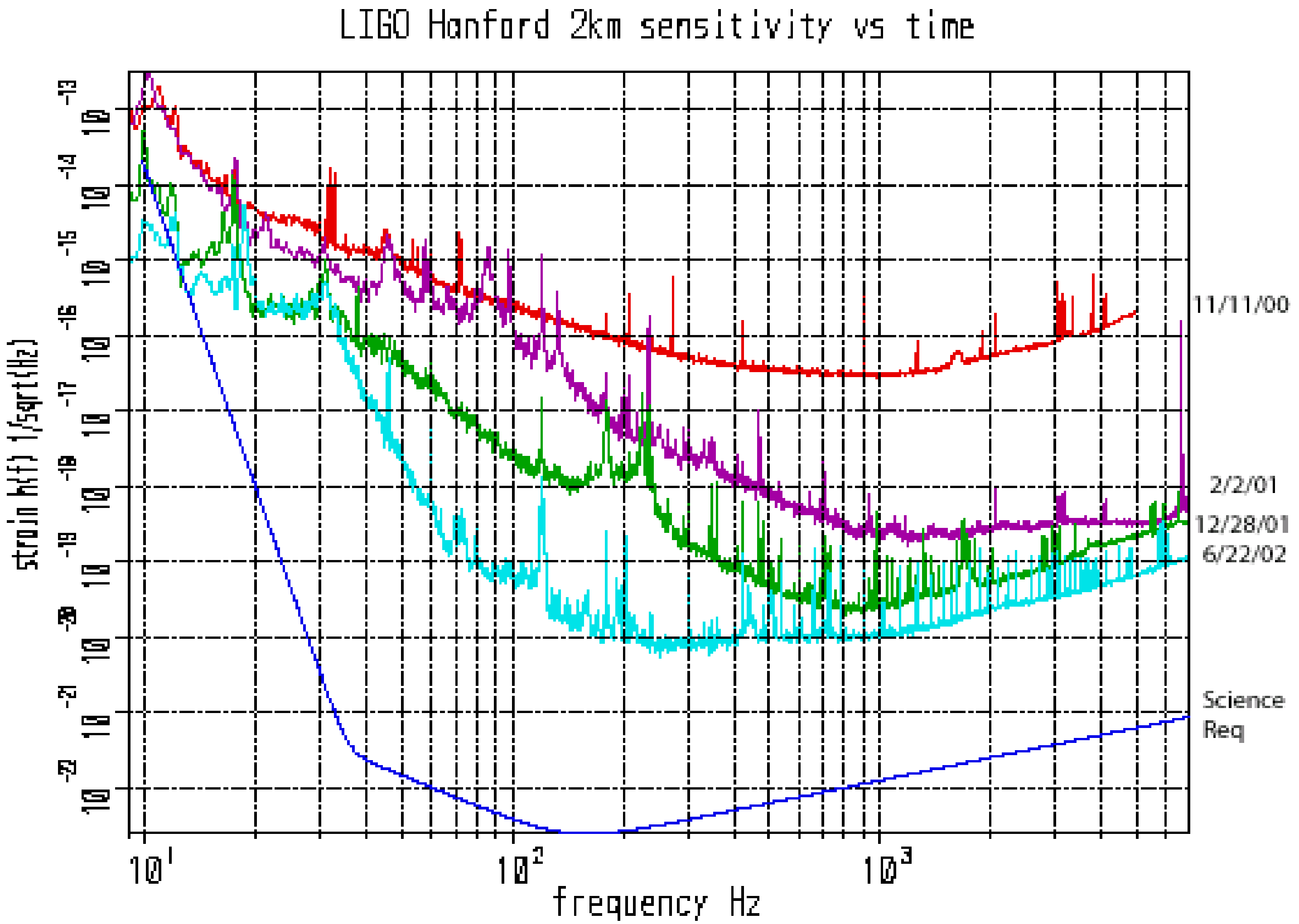
Over the next decade planned program of upgrades and technology development

Current sensitivity of LIGOs



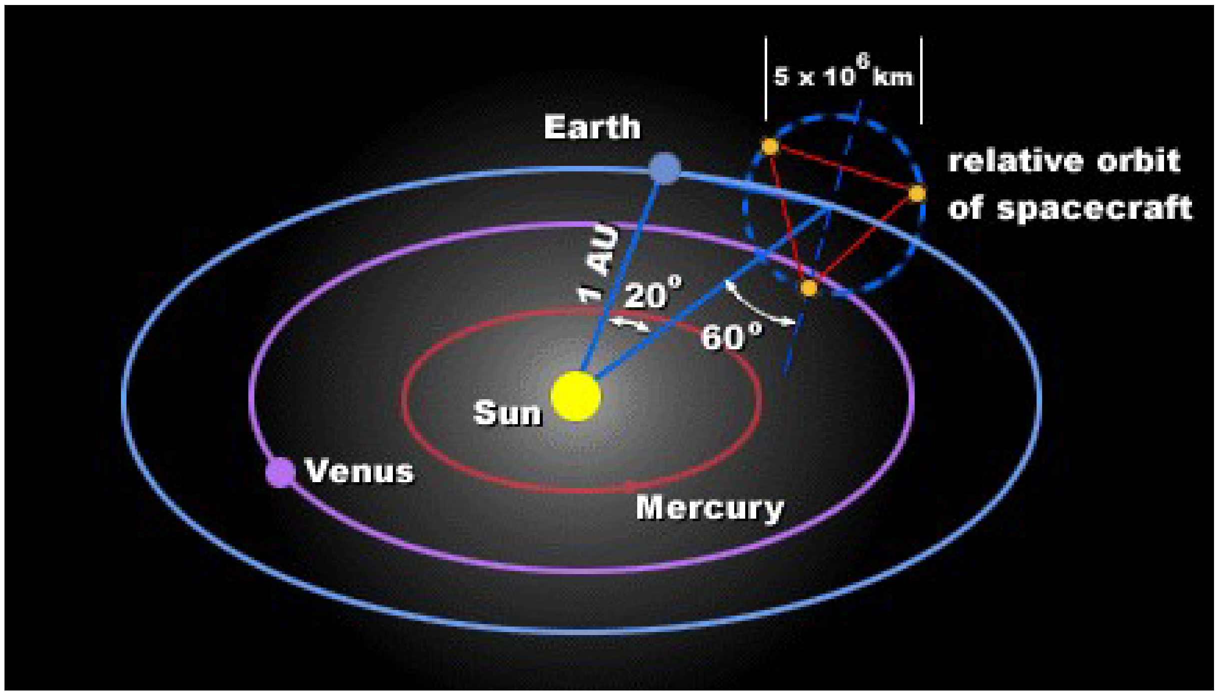
[Courtesy of B Barish]

Sensitivity in time of 2Km-LIGO in Hanford



Laser Interferometer Space Antenna (frequency band: $10^{-4} - 0.1$ Hz)

ESA/NASA mission in 2011 (?)



Characteristic intensity and frequency of relic gravitational waves

- **The intensity**

$$\Omega_{\rm GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\log f} = \frac{4\pi^2}{3H_0^2}\, f^3\, S_h(f)$$

$$\rho_{GW} = \frac{1}{32\pi G}\,\overline{\dot{h}_{ij}(t)\,\dot{h}_{ij}(t)} \qquad 2\int df\, S_h(f) = \langle h_{ij}(t)\, h_{ij}(t)\rangle$$

  – **Phenomenological bounds**

- **Two features determine the typical frequencies: the *dynamics* of production mechanism which is model dependent, and the *kinematics*, i.e. the redshift from the production era**

  – **Suppose a graviton is produced at time t_* with frequency f_* during RD or MD era**

$$f_0 = f_*\, a(t_*)/a(t_0), \quad g\, a^3\, T^3 = \text{const.}, \quad 1/f_* = \lambda_* = \epsilon\, H_*^{-1}$$

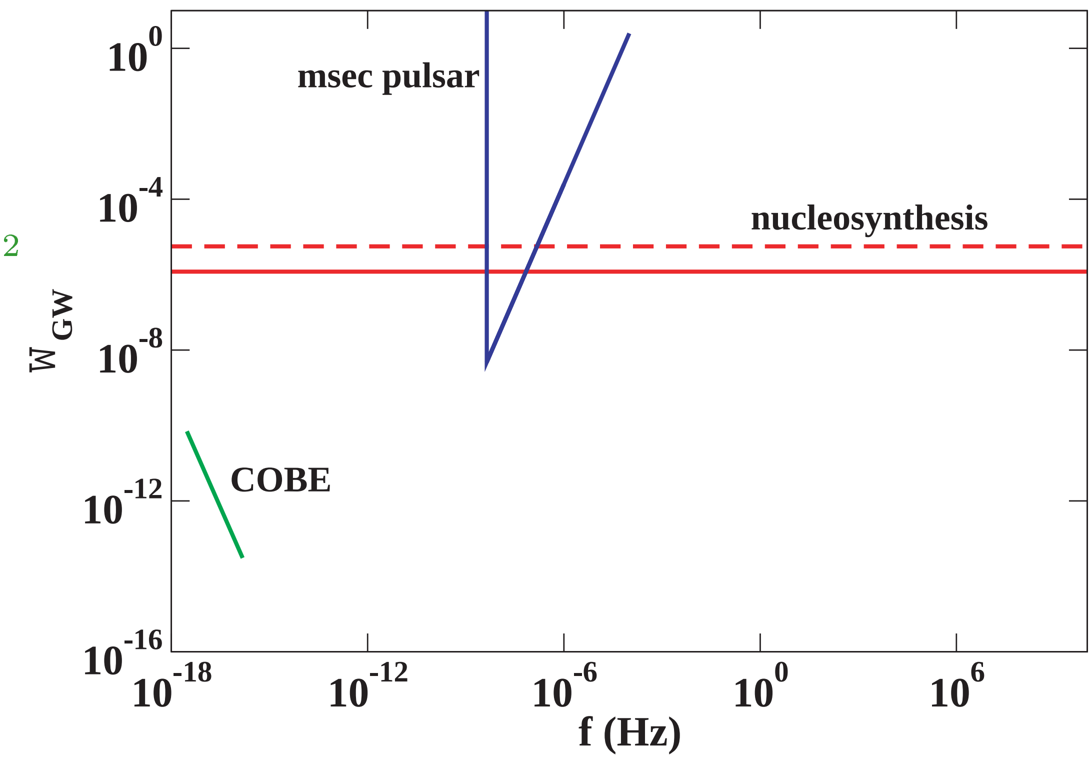
$$f_0 \simeq 10^{-7}\,\frac{1}{\epsilon}\,\left(\frac{T_*}{1\,\text{GeV}}\right)\,\left(\frac{g_*}{100}\right)^{1/6}\,\text{Hz}$$ [Kamionkowski, Kosowski & Turner 94; Maggiore 00]

Phenomenological bounds

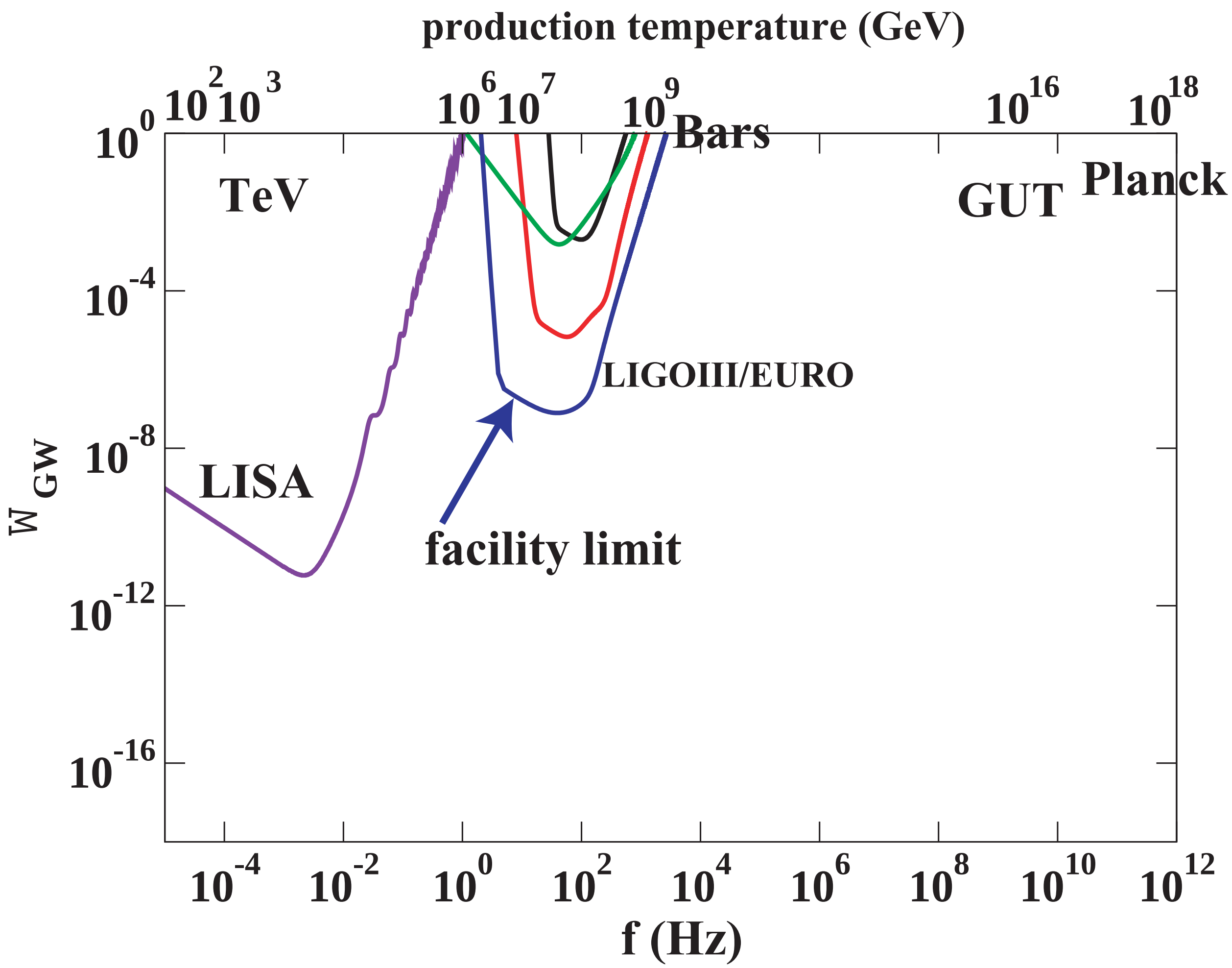
- $\int h_0^2\, \Omega_{\mathrm{GW}}(f)\, d\log f \leq$
  $5.6 \times 10^{-6}\, (N_\nu - 3)$

- $h_0^2\, \Omega_{\mathrm{GW}}(f) \leq 7 \times 10^{-11}\ \left(\frac{H_0}{f}\right)^2$
  $H_0 \leq f \leq 10^{-16}$ Hz

- $h_0^2\, \Omega_{\mathrm{GW}}(f_*) \leq 10^{-8}$
  $f_* = 4.4 \times 10^{-9}$ Hz



Typical temperatures probe by GWs produced by *causal* mechanisms



Stochastic GW background from *standard* inflation

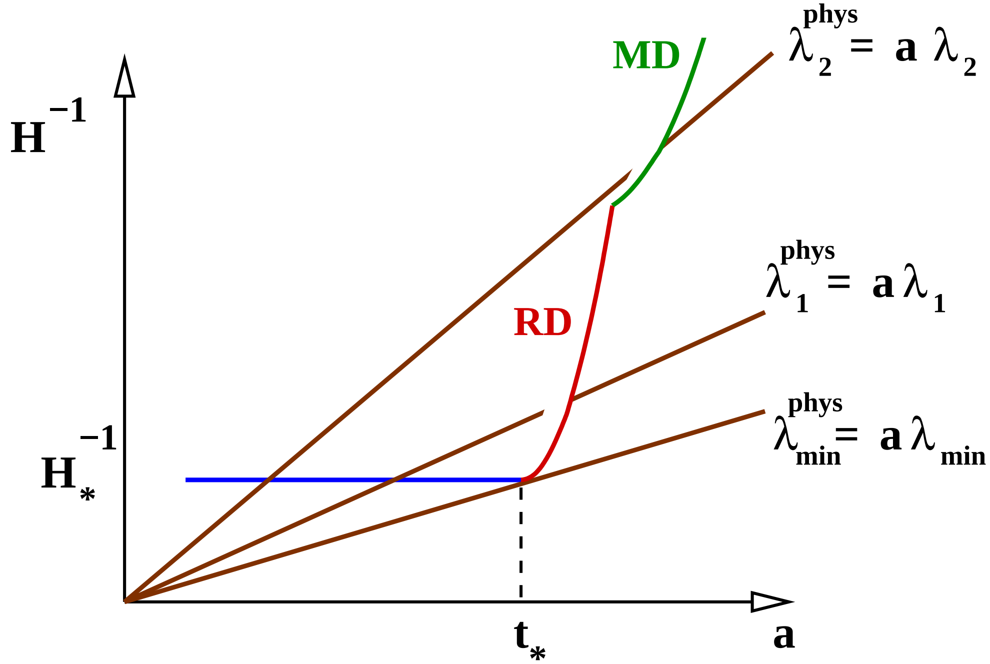
In *standard* inflationary models Hubble parameter almost constant

- $2\pi f_* H_*^{-1} \ll 1 \Rightarrow$ **abrupt transition**
  $\Rightarrow$ production of particles out of vacuum

- $2\pi f_* H_*^{-1} \gg 1 \Rightarrow$ **adiabatic transition**
  $\Rightarrow$ no production of particles

$h_0^2 \Omega_{\rm GW}(f) \sim f^{n_T} \quad |n_T| \ll 1$

cutoff frequency $f_*^{\rm max} \sim H_*/2\pi$



Inflation: $H^{-1} \simeq \text{const.}$

RD: $H^{-1} \propto a^2$

MD: $H^{-1} \propto a^{3/2}$

Example: Slow-roll inflation

$$n_T = -\frac{m_{\rm Pl}}{8\pi}\left(\frac{V'_\bullet}{V_\bullet}\right)^2$$

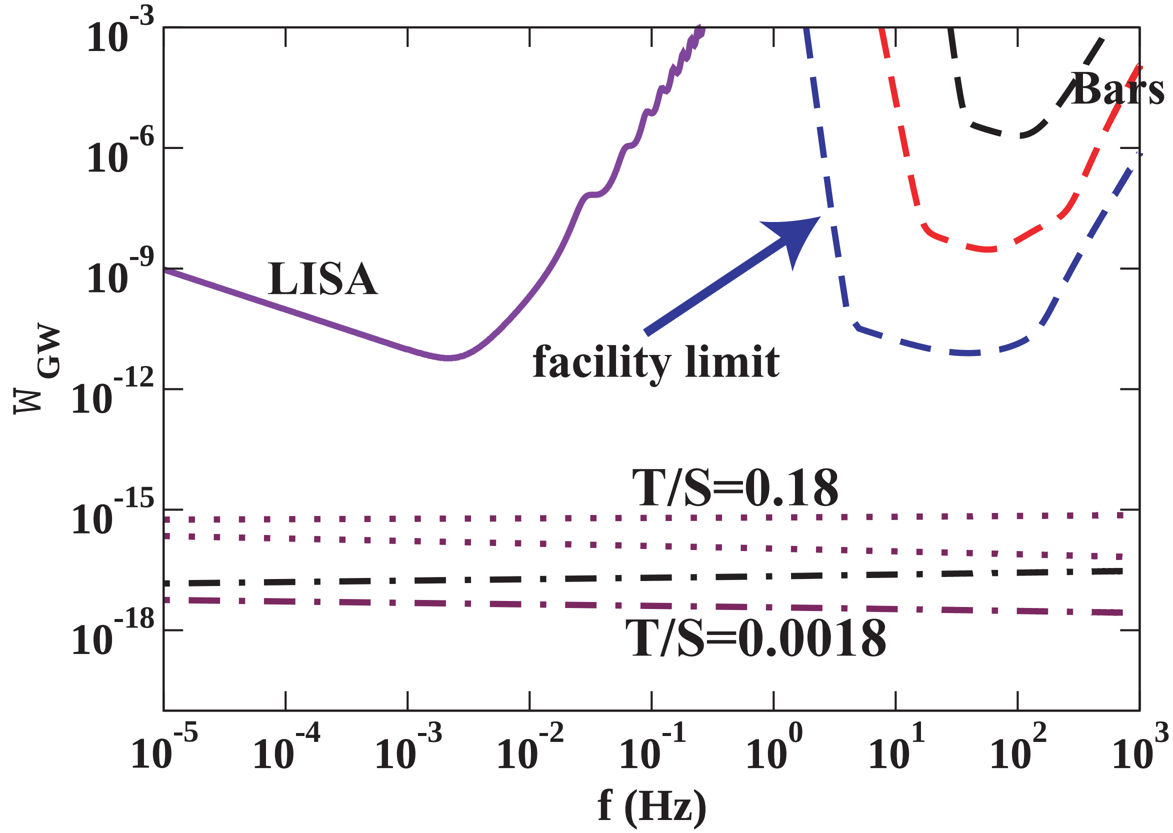
$$S \equiv \frac{5\langle|a^S_{2m}|^2\rangle}{4\pi}$$

$$T \equiv \frac{5\langle|a^T_{2m}|^2\rangle}{4\pi} = 0.61\left(\frac{V_\bullet}{m^4_{\rm Pl}}\right)$$

$$n_T = -\frac{1}{7}\frac{T}{S}$$

$$\frac{dn_T}{d\log k} = -n_T\left(\frac{V'_\bullet}{V_\bullet}\right)'$$

[Turner 97]



Sensitivity enhanced by correlating earth-based detectors

Post-LISA mission?

To avoid the galactic-binary noise

the "knee" should be around 0.1 Hz

But extragalactic-binary noise

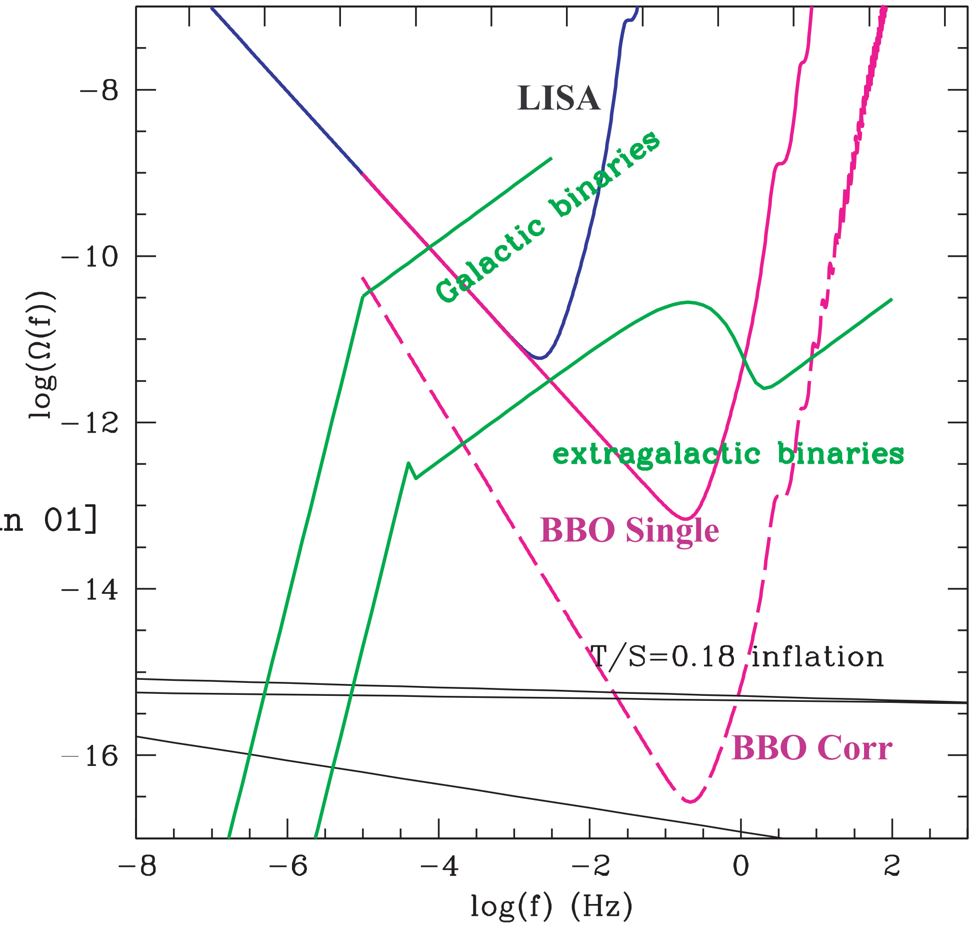
should be subtracted too

[Ungarelli & Vecchio 00,01; Bender & Hogan 01]

[Seto, Kawamura & Nakamura 01]

Big Bang Observatory (?)

[Folkner & Phinney]

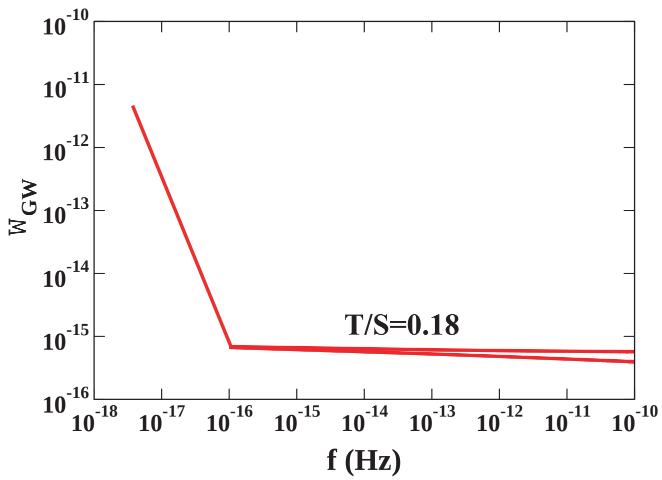


[Courtesy of S Phinney]

Imprints of relic gravitational waves on CMB

$$S \equiv \frac{5\langle|a^S_{2m}|^2\rangle}{4\pi}$$

$$T \equiv \frac{5\langle|a^T_{2m}|^2\rangle}{4\pi} = 0.61\left(\frac{V_\bullet}{m^4_{\rm Pl}}\right)$$



Temperature map can measure

$T/S \gtrsim 0.1$ but not less

- **Measuring polarization of CMB**

[Kamionkowski, Kosowsky & Stebbins 97; Seljak & Zaldarriaga 97; Kamionkowski & Kosowsky 98]

– Only tensor fluctuations contribute to the curl

– Contamination due to weak gravitational lensing of CMB along the line of sight

[Knox & Song 02; Kesden, Cooray & Kamionkowski 02]

–Minimum detectable inflation-energy $V_\bullet^{1/4} > 10^{15}$ GeV with $s = 1\mu{\rm K}\sqrt{\rm sec}$

[CMB detectors beyond Planck]

Plethora of inflationary models $\rightarrow$ possibility of discriminating among them

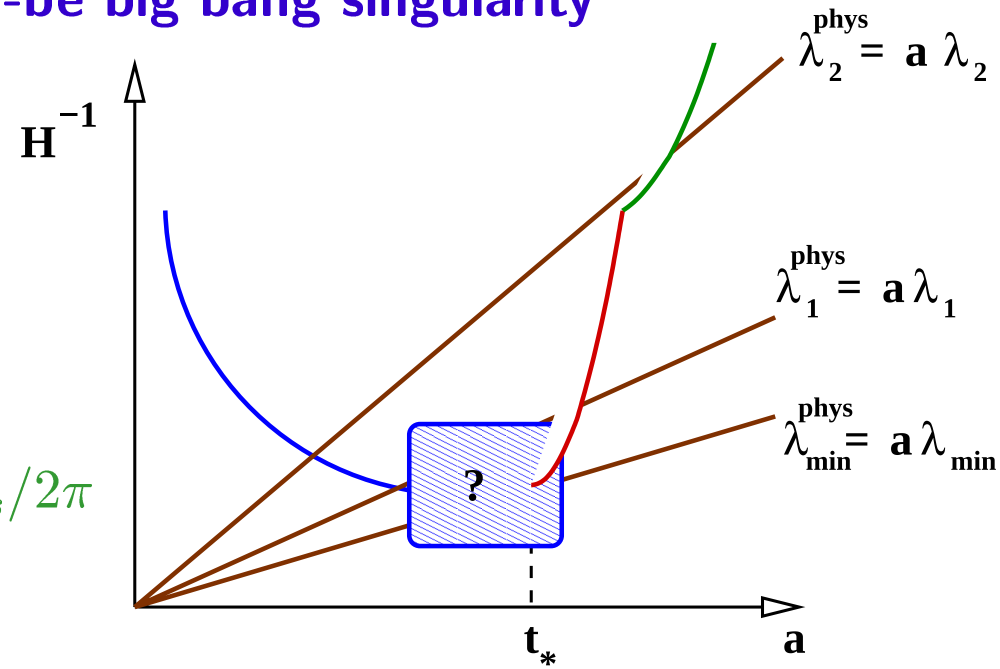
Stochastic GW background from string-theory– inspired models

In some string-inspired inflationary models, such as pre-big bang [Gasperini & Veneziano 93] and ekpyrotic scenarios [Khoury et al. 00] Hubble parameter grows toward the would-be big bang singularity

GW spectrum is blue at low frequency ⇒ no contribution to CMB

$h_0^2\,\Omega_{\rm GW}(f) \sim f^n$

cutoff frequency $f_*^{\rm max} \sim H_*/2\pi \sim H_s/2\pi$



Warnings:

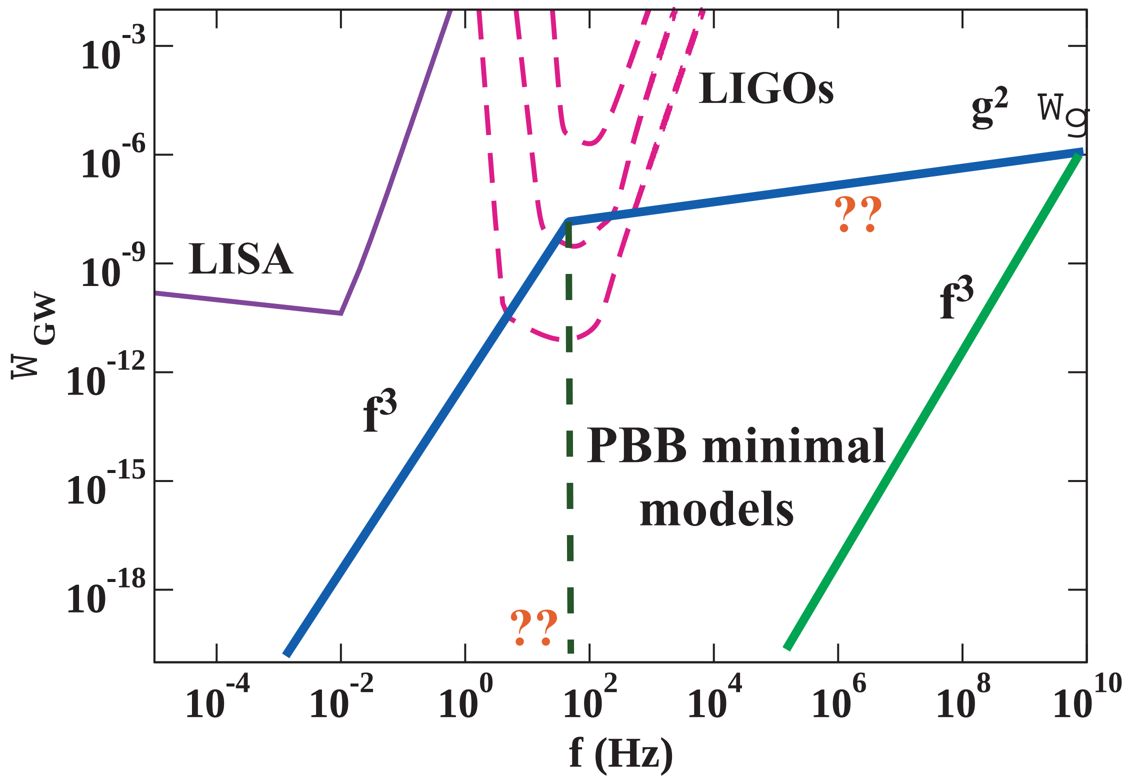
– So far, those models did not provide a description of the transition

– GW spectrum could be affected by details of transition

String-inspired models

In non-minimal models the spectrum at high frequency can also be red

[Gasperini & Veneziano 02]



Stochastic GW background from *non standard* cosmological phases

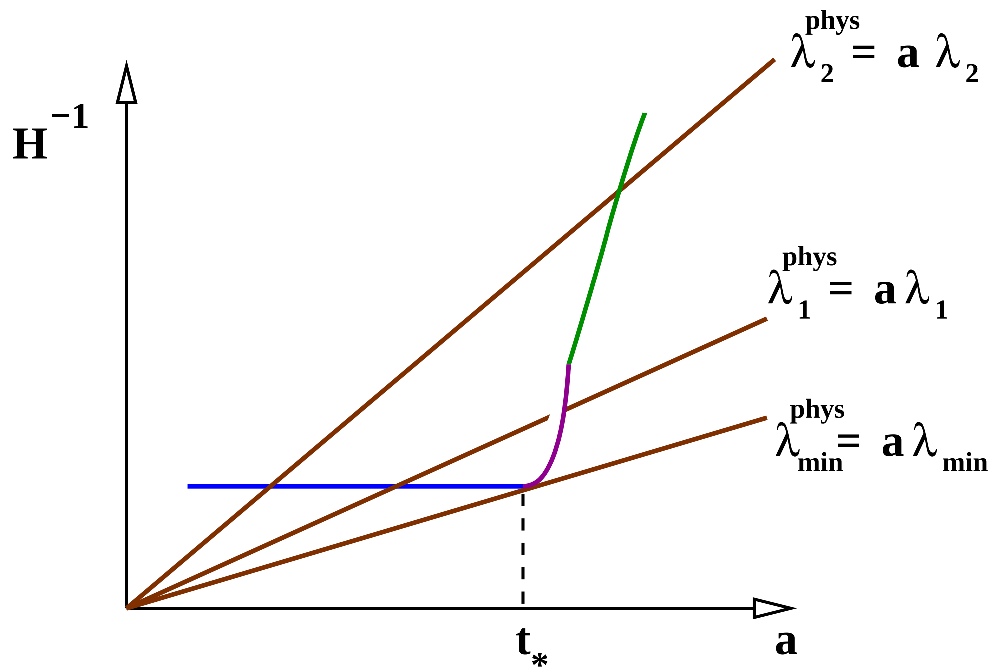
In some models the inflationary era is not followed immediately by the radiation era but rather by an expanding phase whose equation of state is stiffer than radiation [Grishchuk 75]

stiff era: $H^{-1} \propto a^3$

GW spectrum at high frequency can be blue

$h_0^2\,\Omega_{\rm GW}(f) \sim f$

cutoff frequency $f_*^{\rm max} \sim H_*/2\pi$



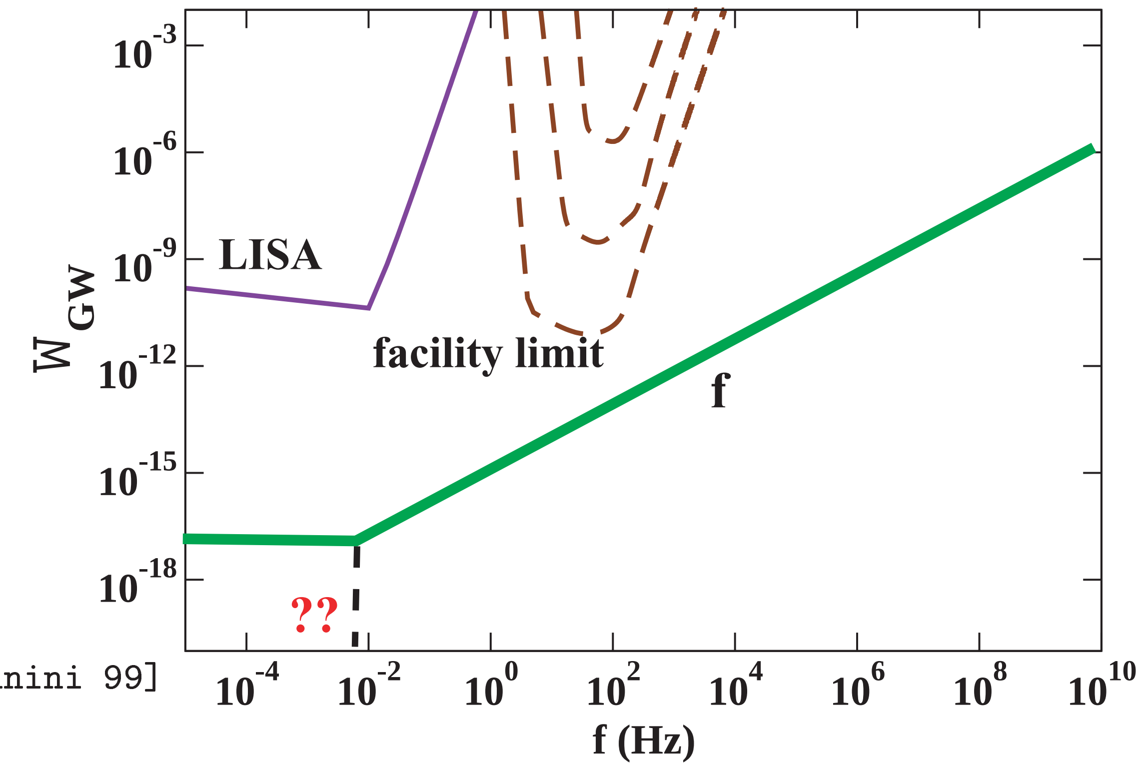
— Quintessential inflation [Peebles & Vilenkin 98; Giovannini 99]

— Brane world inflation [Sahni, Sami & Souradeep 99]

"Spikes" in the GW spectrum

Reheating occurs through amplification of quantum vacuum fluctuations

[Giovannini 99; Babusci & Giovannini 99]

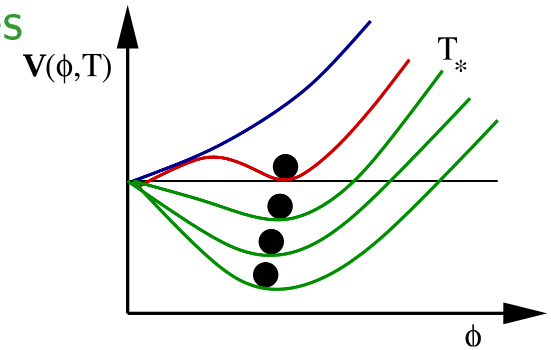


Electromagnetic detectors in MHz or GHz region?

Gravitational waves from first-order phase transitions

Via quantum tunnelling true vacuum bubbles nucleates

When bubbles collide $\Rightarrow$ emission of gravitational waves



$\beta \longrightarrow$ bubble nucleation rate per unit volume

$\alpha \longrightarrow$ jump in energy density experienced by order parameter

EW phase transition: $T_* \simeq 100\,\mathrm{GeV}$ and $\beta/H_* \simeq 10^2$–10^3

$\Rightarrow f_{\rm peak} \simeq 10^{-4}$–$5 \times 10^{-3}$Hz

Intensity of GW spectrum: $h_0^2\,\Omega_{\rm GW} \simeq 10^{-6}\,(H_*/\beta)^2\,f(\alpha, v)$

– In SM there is *no* first-order EW phase transition for Higgs mass larger then M_w

– In MSSM, for certain values of Higgs mass, there are possibilities but $h_0^2\,\Omega_{\rm GW} \lesssim 10^{-16}$

[Kosowsky & Turner 94; Kosowsky, Turner & Kamionkowski 94]

– In NMSSM: $h_0^2\,\Omega_{\rm GW} \;\leq\; 10^{-15}$–$10^{-10}$ with $f_{\rm peak} \simeq 10$mHz

[Apreda, Maggiore, Nicolis & Riotto 01]

"Burst" of GWs from the early Universe

- GWs from bubble collision in extended inflation

$h_0^2\,\Omega_{\rm GW} \sim 10^{-5}$

at $f \sim 10^2 \left(\frac{T_{RH}}{10^{10}\,{\rm GeV}}\right)$

[Turner & Wilczek 90]

- GWs from cosmological turbulence

[Kosowsky et al.; Apreda et al. 01]

- GWs produced after preheating

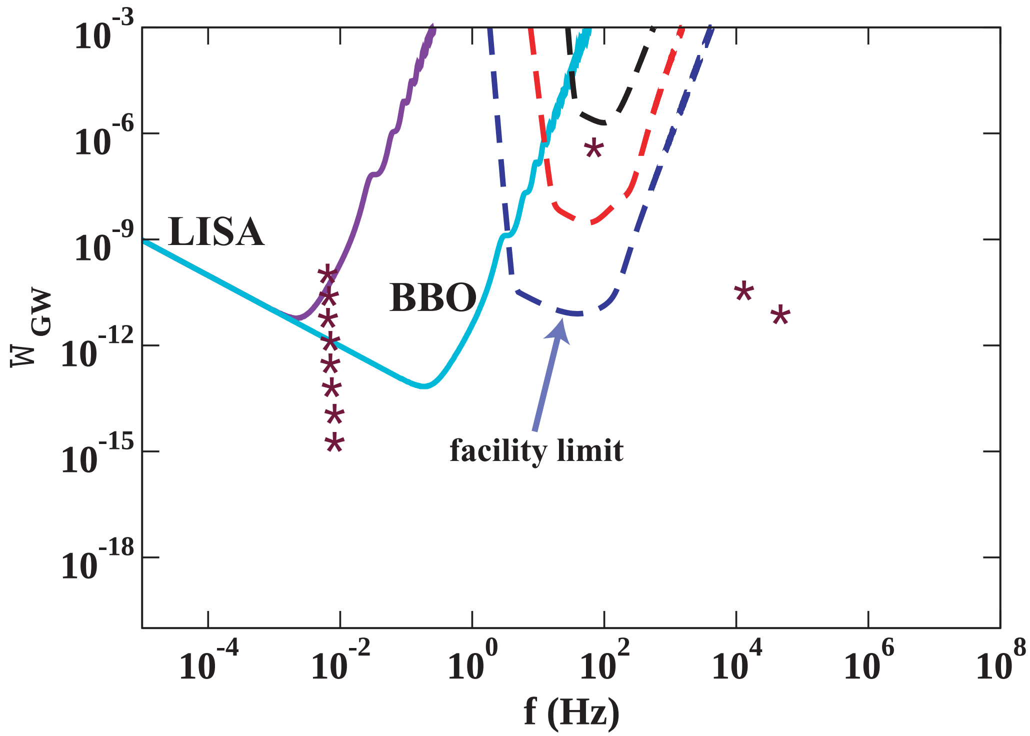
$V(\phi) \sim \phi^2\,\chi^2$:

$h_0^2\,\Omega_{\rm GW} \sim 10^{-12}$ at $f \sim 10^5$Hz

$V(\phi) \sim \lambda\,\phi^4$:

$h_0^2\,\Omega_{\rm GW} \sim 10^{-11}$ at $f \sim 10^4$Hz

[Khlebnikov & Thachev 97]



Gravitational waves from cosmic strings

Topological defects formed at phase transitions

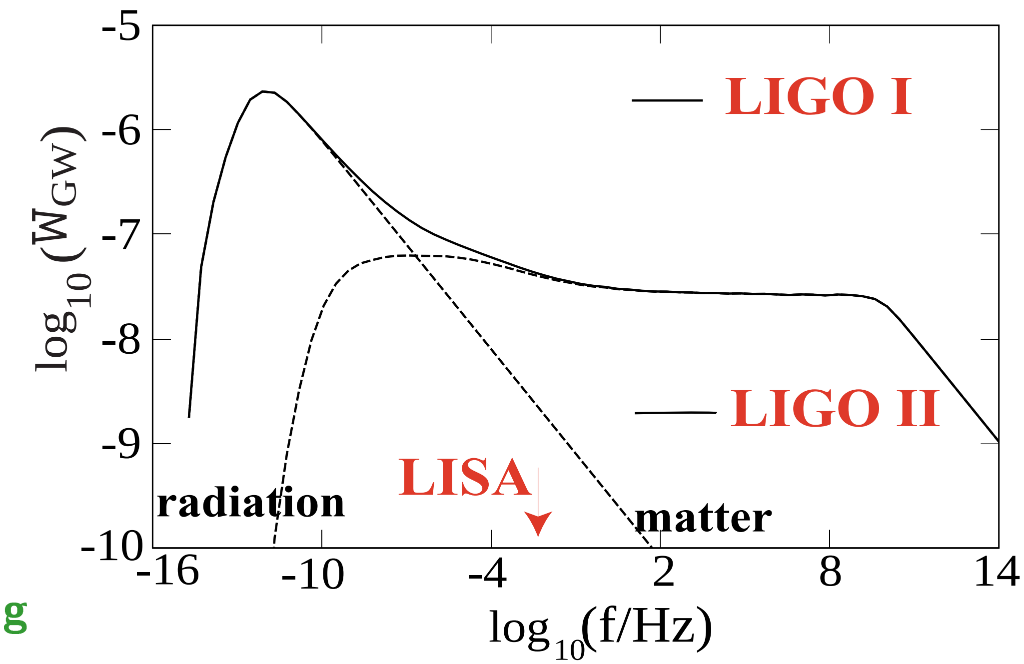
- They have large tension μ, they oscillate relativistically and emit GWs [Vilenkin 81]
- Scaling property characterizes the dynamics of string network $\Rightarrow$ stochastic background of GWs extends on very large frequency band and almost flat (in LISA/LIGO band)

$h_0^2\,\Omega_{\rm GW} \sim 10^{-8}$–$10^{-7}$
at $10^{-4}\,{\rm Hz} \leq f \leq 10^3\,{\rm Hz}$

Loop radiates with power $P \sim \Gamma\, G\, \mu^2$
$h_0^2\,\Omega_{\rm GW} \sim P/\rho_c \sim \Gamma\, G^2\, \mu^2$
$(G\,\mu)_{\rm GUT} \sim 10^{-6}$ and $\Gamma \sim 50$

$G\,\mu$ constrained by msec pulsar timing

[Caldwell, Battye & Shellard 96]



[from B Allen 96]

GWs bursts from cosmic strings for earth-based detectors

The stochastic ensemble of GWs from network of oscillating loops can be strongly non Gaussian and it includes sharp bursts emanating from cusps and kinks [Damour & Vilenkin 00,01]

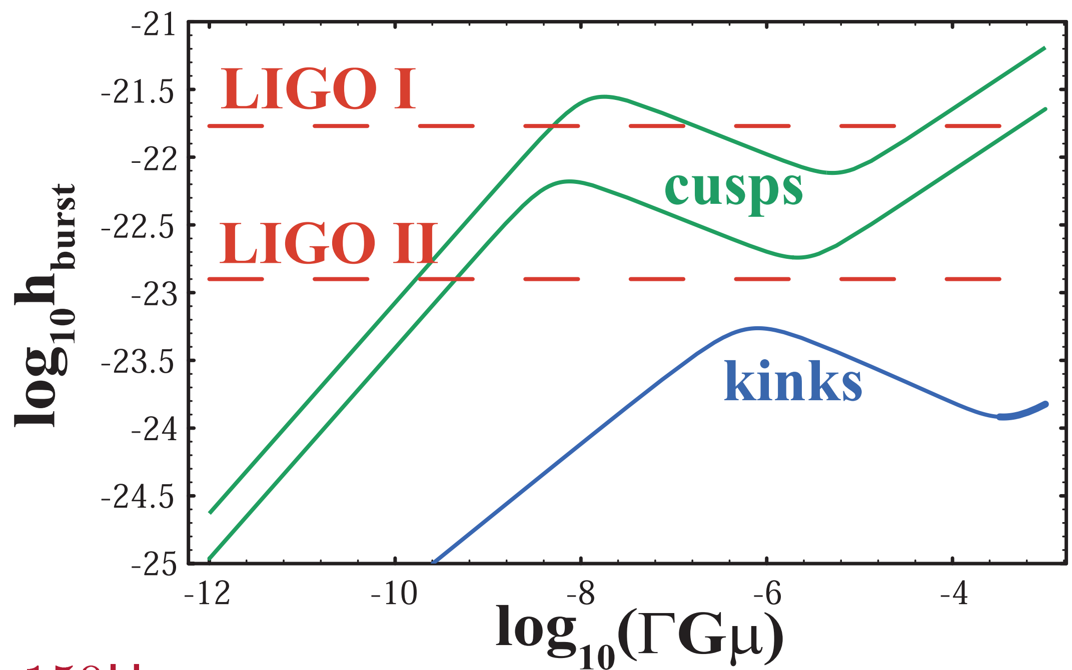
Assumptions:

Typical lenght of loop: $l \sim \alpha\, t$

Typical number density of loops:

$n_l \sim \alpha^{-1}\, t^{-3}$

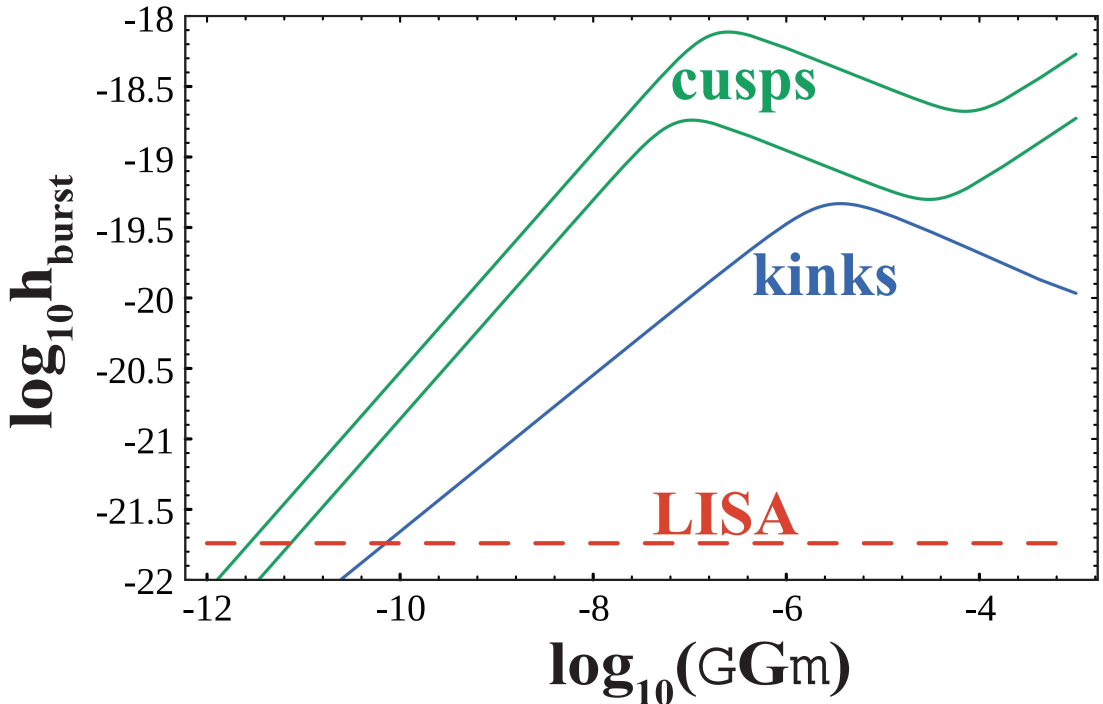
$\alpha \sim \Gamma\, G\, \mu$



$f_{\rm opt} = 150$Hz

from T Damour & A Vilenkin 01

GWs bursts from cosmic strings for LISA



$f_{\rm opt} = 3.9 \times 10^{-3}$Hz

from T Damour & A Vilenkin 01

Determining cosmological parameters by measuring GWs

- Binary systems as "standard candles" (Measurement of H_0) [Schutz 86,89]

$$\frac{S}{N} \propto \Theta\,\zeta\,f(\mathcal{M})/d_L(z,\Omega_M,\Omega_\Lambda,\ldots) \quad \mathcal{M} = \mathcal{M}_0\,(1+z)$$

– By using three earth-based interferometers it is possible to determine the location of the binary, its parameters, the cosmological distance but not the redshift!

– Redshift could be inferred from EM wave associated to GW. But then we can limit only to fairly nearby binaries

- Without using EM counterpart, and using advanced detectors, cosmological parameters can be estimated to 10–40% [Schutz & Krolak 87; Marković 93]

- For NS/NS binaries, distribution of observed events has sizeable dependence on the cosmological constant [Wang & Turner 97]

- Using EM counterpart, extracting cosmological parameters by mapping massive binary–black-hole mergers at $z \sim 1$–10 with LISA [Holz, Hughes & Larson, in preparation]

Brane world scenarios: new effects?

- **Gravitational Lorentz violation** [Csáki, Erlich & Grojean 01]
  - Asymmetric warped spacetime: the local speed of light depends on the position along the extra dimension
  - The GWs propagate in the bulk and *feel* the variation of the speed of light
  - $(c_g - c_\gamma)$ could be measured by detecting GWs and EM waves from supernovae or γ-ray bursts, but it is crucial (not at all easy!) to know the time delay between GW and EM wave
- **Excitations of radion and brane's displacements should peak at frequency** [Hogan 00]

$$f_{\rm peak} \sim 10^{-4}\,{\rm Hz}\,\left(\frac{1mm}{b}\right)^{1/2}$$

- **GWs from brane world cosmology**

  Evolution of metric perturbations on the brane coupled to evolution of the bulk. Very complicated to separate the zero-mode, corresponding to a massless graviton on the brane, from the massive states. [Special case investigated by Langlois, Maartens & Wands 00]

Comments

- **The search for GWs from the early Universe is very challenging but the outcome is worth the affort**

- **By detecting relic GWs we will be able to discriminate between inflationary models, know how inflation ended, if phase transitions occured, if cosmic strings existed and have an independent estimation of cosmological parameters**

- **Maybe, if nature is kind with us we won't wait for a long time. There could be surprises.**

- **Earth-based and space interferometers much more sensitive to GWs from astrophysical sources, such as binary BHs, NS/BH, NSs, supermassive black holes, pulsars low-mass X-ray binaries, etc.**

Science in LIGO-I/Virgo and LIGO-II

BH of mass 10 $M_\odot$

NS of mass 1.4 $M_\odot$